Where the Wild Things Are: Observational Constraints on Black Holes' Growth

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Abstract. The physical and evolutionary relation between growing supermassive black holes (AGN) and host galaxies is currently the subject of intense research activity. Nevertheless, a deep theoretical understanding of such a relation is hampered by the unique multi-scale nature of the combined AGN-galaxy system, which defies any purely numerical, or semi-analytic approach. Various physical process active on different scales have signatures in different parts of the electromagnetic spectrum; thus, observations at different wavelengths and theoretical ideas all should contribute towards a "large dynamic range" view of the AGN phenomenon. As an example, I will focus in this review on two major recent observational results on the cosmic evolution of supermassive black holes, focusing on the novel contribution given to the field by the COSMOS survey. First of all, I will discuss the evidence for the so-called "downsizing" in the AGN population as derived from large X-ray surveys. I will then present new constraints on the evolution of the black hole-galaxy scaling relation at $1 < z < 2$ derived by exploiting the full multi-wavelength coverage of the survey on a complete sample of $\sim$90 type 1 AGN.

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INTRODUCTION

In the past decade three seminal discoveries have revealed tight links and feedback loops between the growth of nuclear super-massive black holes and galaxy evolution, promoting a true shift of paradigm in our view of black hole astrophysics, which have moved from the role of exotic tracers (the 'Wild Things') of cosmic structures to that of fundamental ingredients of them.

First of all, the search for the local QSO relics via the study of their dynamical influence on the surrounding stars and gas led to the discovery of SMBH in the center of most nearby bulge-dominated galaxies. The steep and tight correlations between their masses and bulge properties (so-called *scaling relations*; [1, 2, 3]) represented the first and fundamental piece of evidence in favor of a connection between galaxy evolution and central black holes. The second one stems from the fact that SMBH growth is now known to be due to radiatively efficient accretion over cosmological times, taking place during "active" phases [4, 5] (hereafter MH08). If most galaxies host a SMBH today, they should have experienced such a phase of strong nuclear activity in the past. Finally, extensive programs of optical and NIR follow-up observations of X-ray selected AGN in the *Chandra* and *XMM-Newton* era put on solid grounds the evolution of accretion luminosity over a significant fraction of cosmic time. We have thus discovered that lower luminosity AGN peak at a lower redshift than luminous QSOs [see e.g. 6]. Such a

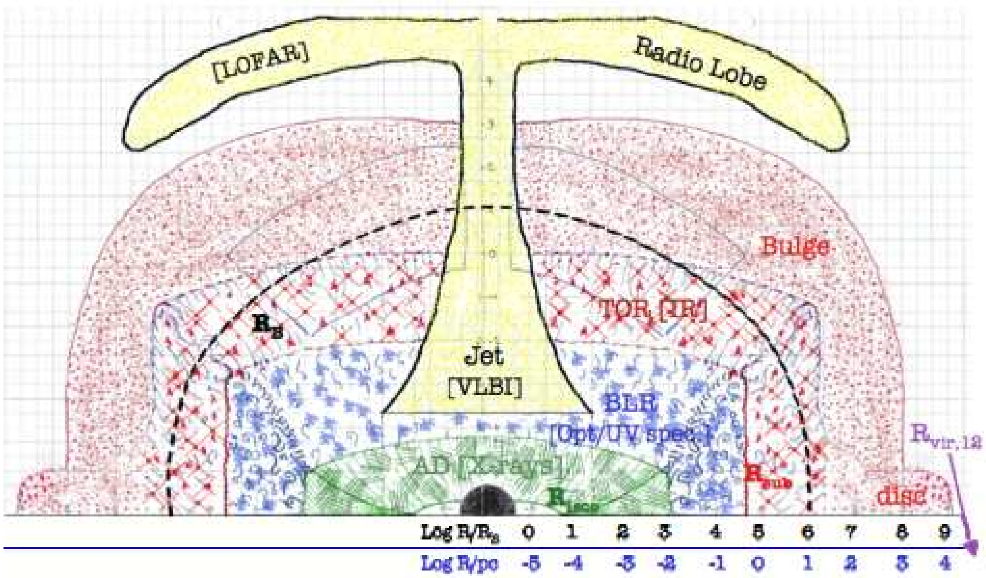

FIGURE 1. A schematic, logarithmic view of an AGN-galaxy system. Scales on the bottom axes are in units of Schwarzschild radii and parsec, and are approximately inferred for a $\sim 10^{11} M_\odot$ galaxy containing a $\sim 10^8 M_\odot$ black hole. Here, $R_{\rm vir,12}$ is the virial radius of a $10^{12} M_\odot$ dark matter halo, $R_{\rm B}$ stands for the Bondi radius (marked also by a thick dashed line), $R_{\rm sub}$ and $R_{\rm ISCO}$ for the dust sublimation radius and the innermost stable circular orbit ($\sim$inner edge of the accretion disc), respectively. The logarithmic scales at the bottom are in units of Schwarzschild radii ($R_{\rm S}$) and parsec, respectively. See text for details.

behavior is analogous to that observed for star formation (usually referred to as "cosmic downsizing") lending a third, independent, support to the idea that the formation and evolution of SMBHs and their host galaxies might be closely related.

Such a shift of paradigm has sparkled the activity of theoretical modelers. Following early pioneering analytic works [7, 8], widely different approaches have been taken to study the role of AGN in galaxy evolution. Semi-analytic models (SAM) have been the more numerous [see e.g. 9], and, despite their huge freedom in the exploration of parameter spaces, have helped establishing the importance of late-time feedback from radio active AGN for the high-mass end of the galaxy mass function. On the other hand, fully hydrodynamic simulations of cosmological BH have been performed [see e.g. 10], but their computational costs have so far allowed only a limited exploration of sub-grid prescriptions. A third, hybrid, approach has also been followed, in which the results of high-resolution simulations of galaxy-galaxy mergers with black holes [11] have been used to construct a general framework for merger-induced AGN feedback [12]. The combination of these approaches has sharpened our view of the SMBH-galaxy co-evolution, but none of them can be considered self-sufficient in such a heavily observation-driven field of astrophysics. The reason for this bottleneck is the unique multi-scale nature of the problem at hand, which defies any current (and foreseeable) purely numerical, or semi-analytic approach.

Let us illustrate this point schematically. An AGN releases most of its energy (radiative or kinetic) on the scale of a few Schwarzschild radii ($\sim 10^{-5}$ pc for a $10^8 M_\odot$ BH), while the mass inflow rate (accretion rate) is set at the Bondi radius, some 10^4 times

further out; broad permitted atomic emission lines, used to estimate SMBH masses in QSOs, are produced at ∼0.1 pc; on a scale of a parsec, and outside the sublimation radius, a dusty, large-scaleheight, possibly clumpy, medium obscures the view of the inner engine [13] crucially determining the observational properties of the AGN [14]; on the same scale, powerful star formation might be triggered by the self-gravitational instability of the inflowing gas; finally, AGN feedback must be operative on the galaxy scale ($\sim$ a few kpc, some $\sim 10^8$ times R_S!) in order to have an appreciable effect on its global structural properties. A schematic logarithmic map of a AGN-galaxy system is shown in Fig. 1, where I have highlighted the various physical regions of crucial interest and the wavelength ranges where the associated emission takes mostly place. Bringing all of the above into a coherent framework is indeed a formidable challenge. In fact, each physical process active on each different physical scale has a signature in a different part of the electromagnetic spectrum (so that different instruments are needed to unveil it). Observations at different wavelengths and theoretical ideas all contribute towards a "large dynamic range" view of the AGN phenomenon, capable of conceptually "resolving" the many physical scales involved.

In this review, I'd like to show two specific examples of how deep, multi-wavelength surveys can be used to deepen our knowledge of the AGN phenomenon, of its evolution over cosmic time, and of its relationship with the evolution of the galaxies they are embedded in. In particular, most of the recent results shown here are part of the large collaborative effort known as the COSMOS survey (`http://cosmos.astro.caltech.edu/`).

WILD THINGS IN THE COSMOS

The Cosmic Evolution Survey (COSMOS) field [15] is a so far unique area for deep and wide comprehensive multiwavelength coverage, from the optical band with *HST, Subaru* and other ground based telescopes, to the IR (*Spitzer*), and X-rays with *XMM-Newton* and *Chandra*, to the radio with the *VLA*. The spectroscopic coverage with *VIMOS/VLT* (zCOSMOS; [16]) and *IMACS/Magellan*, coupled with the reliable photometric redshifts derived from multi-band fitting allow us to build a large and homogeneous sample of both obscured and un-obscured AGN with dense spectral coverage, to estimate the effects of intrinsic reddening and to keep under control selection effects.

I have chosen to focus here on just two among the many recent COSMOS results in the field of AGN, in order to illustrate the power and versatility of this kind of surveys. First of all, I will show how the very high level of (spectroscopic plus photometric) redshift completeness of the X-ray selected AGN samples allows an exquisite determination of the AGN luminosity function evolution, and how, coupling such a study with basic theoretical consideration on how black holes evolve over cosmological times (via a continuity equation), we can study in great details the downsizing phenomenon for AGN. Second, I will briefly mention recent progresses made on the study of the cosmological evolution of the scaling relations between black holes and host galaxies made possible by the intensive multi-wavelength coverage of the COSMOS field.

Dissecting AGN downsizing

The term *downsizing* was first used by Cowie et al. [17] to describe their finding that actively star-forming galaxies at low redshift have smaller masses than actively star-forming galaxies at $z \sim 1$. In the current cosmology jargon, this term has come to identify a variety of possibly distinct phenomena, not just related to the epoch of star formation, but also to that of star formation quenching, or galaxy assembly (see the discussion in Faber et al. [18], and references therein).

Given this growing body of observational evidence, it is legitimate to ask whether black holes and AGN do also show a similar trend. The first hints of a positive answer came from the study of the evolution of the X-ray selected AGN luminosity function. As X-rays are produced very deep in the gravitational potential of a black hole, they are the best probes of the accretion energy release (modulo the effect of obscuration). In the last decade, we have thus learned that more luminous AGN were more common in the past, with the X-ray luminosity function (XLF) following a so-called 'Luminosity Density Dependent Evolution' [19, 6]. These works were all based on a combination of a large number of X-ray surveys of different depth and area. Now the XMM-COSMOS survey [20] *alone*, thanks to its very high spectroscopic completeness over a relatively large area of the sky, can be used to provide new constraints on the XLF, especially at $z > 3$ [21]. The left panel of Figure 2 (Miyaji et al. in prep.) shows the number density evolution of X-ray selected AGN of different luminosities obtained from COSMOS data *only*, where one can clearly see how more luminous AGN were more common in the past as compared to lower luminosity ones, a direct phenomenological manifestation of AGN downsizing. How can we use this (and other analogous) results on the XLF evolution to gain further insights on the physical evolution of the black hole population?

As opposed to the case of galaxies, where the direct relationship between the evolving mass functions of the various morphological types and the distribution of star forming galaxies is not straightforward due to the never-ending morphological and photometric transformation of the different populations, the situation in the case of SMBH is much simpler. For the latter case, we can assume their evolution is governed by a continuity equation (MH08, and references therein), where the mass function of SMBH at any given time can be used to predict that at any other time, provided the distribution of accretion rates as a function of black hole mass is known. Such equation can be written as:

$$\frac{\partial \psi(\mu,t)}{\partial t} + \frac{\partial}{\partial \mu}\left(\psi(\mu,t)\langle \dot{M}(\mu,t)\rangle\right) = 0 \qquad (1)$$

where $\mu = Log M$ (M is the black hole mass in solar units), $\psi(\mu,t)$ is the SMBH mass function at time t, and $\langle \dot{M}(\mu,t)\rangle$ is the average accretion rate of SMBH of mass M at time t, and can be defined through a "fueling" function, $F(\dot{\mu},\mu,t)$, describing the distribution of accretion rates for objects of mass M at time t: $\langle \dot{M}(M,z)\rangle = \int \dot{M} F(\dot{\mu},\mu,z)\,\mathrm{d}\dot{\mu}$. Such a fueling function is not a priori known, and observational determinations thereof have been able so far to probe robustly only the extremes of the overall population. However, the AGN fueling function can be derived by inverting the integral equation that relates the luminosity function of the population in question with its mass function. Indeed we

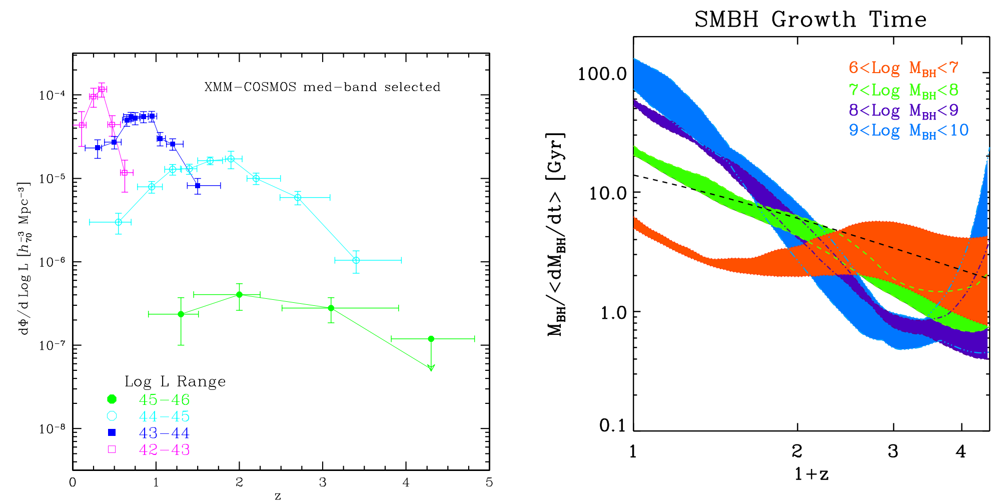

FIGURE 2. **Left**: Number density of 2-10 keV X-ray selected AGN in the XMM-COSMOS field as a function of redshift for different luminosity bins. AGN phenomenological downsizing is evident in the difference between the epochs of peak activity of objects of different luminosity (Miyaji et al., in preparation). **Right**: Average Growth time of Supermassive Black Holes (in years) as a function of redshift for different black hole mass ranges. The dashed line marks the age of the Universe; only black holes with instantaneous growth time smaller than the age of the Universe at any particular redshift can be said to be effectively growing.

can write:

$$\phi(\ell,t) = \int F(\dot{\mu},\mu,t)\,\psi(\mu,t)\,\mathrm{d}\mu \tag{2}$$

where I have called $\ell = Log L_{\mathrm{bol}}$. This is the approach followed in MH08, were the inversion was performed numerically, based on a minimization scheme that used both the X-ray and radio AGN luminosity functions as constraints, complemented by recipes to relate observed (and intrinsic) X-ray and radio (core) luminosities to L_{bol} (see MH08 for details).

Using this approach, we have integrated eq (1) starting from $z = 0$, where we have simultaneous knowledge of both mass, $\psi(\mu)$, and luminosity, $\phi(\ell)$, functions, evolving the SMBH mass function backwards in time, up to where reliable estimates of the (hard X-ray selected) AGN luminosity functions are available (currently this means $z \simeq 4$). The adopted hard X-ray luminosity function is supplemented with luminosity-dependent bolometric corrections of Marconi et al. [4] and absorbing column density distributions consistent with the X-ray background constraints, following the most recent XRB synthesis model (see Gilli et al. [22] for details). Similar results can of course be obtained using directly bolometric luminosity functions (see e.g. Hopkins et al. [23] for a recent attempt to determine $\phi(\ell,t)$).

In this way, we can estimate the specific instantaneous ratio of black hole mass to accretion rate as a function of SMBH mass and its cosmological evolution. Such a ratio defines a timescale, the so-called *growth time*, or mass doubling time (Figure 2, right). The redshift evolution of the growth time distribution can be used to identify the epochs when black holes of different sizes grew the largest fraction of their mass: Black holes

with growth times longer than the age of the Universe are not experiencing a major growth phase, which must have necessarily happened at earlier times. Figure 2 then shows that, while at $z < 0.5 - 1$ only black holes with masses smaller than $10^7 M_{\odot}$ are experiencing significant growth, as we approach the peak of the black hole accretion rate density ($z \sim 1.5 - 2$), we witness the rapid growth of the entire SMBH population. Better constraints on both bolometric luminosity and mass functions evolution are however needed to paint a clearer picture at higher z.

The evolution of scaling relations

Modern multiwavelength surveys are increasingly designed to allow measurements of the physical properties of AGN hosts. Within COSMOS, we have recently studied the hosts of 89 broad line (type–1) Active Galactic Nuclei (AGN) detected in the zCOSMOS survey [16] in the redshift range $1 < z < 2.2$ (for all the details, see Merloni et al. [24]; M09). The unprecedented multi-wavelength coverage of the survey field allowed us to disentangle the emission of the host galaxy from that of the nuclear black hole in their Spectral Energy Distributions (SED). We derive an estimate of black hole masses through the analysis of the broad MgII emission lines observed in the medium-resolution spectra taken with *VIMOS/VLT* as part of the zCOSMOS project. Then, we estimated rest frame K-band luminosity and total stellar mass (and their corresponding uncertainties) of the AGN hosts through an extensive SED fitting procedure, based on large databases of both phenomenological and theoretical galaxy spectra.

We found that, as compared to the local value, the average black hole to host galaxy mass ratio appears to evolve positively with redshift (see Figure 3), with a best fit evolution of the form $(1+z)^{0.74 \pm 0.12^{+0.6}_{-0.3}}$, where the large asymmetric systematic errors stem from the uncertainties in the choice of IMF, in the calibration of the virial relation used to estimate BH masses and in the mean QSO SED adopted. A thorough analysis of observational biases induced by intrinsic scatter in the scaling relations reinforces the conclusion that an evolution of the $M_{\rm BH} - M_*$ relation must ensue for actively growing black holes at early times: either its overall normalization, or its intrinsic scatter (or both) appear to increase with redshift. This can be interpreted as signature of either a more rapid growth of supermassive black holes at high redshift, or a significant mismatch between the typical growth times of nuclear black holes and host galaxies. In both cases, our results provide important clues on the nature of the early co-evolution of black holes and galaxies and challenging tests for models of AGN feedback and self-regulated growth of structures.

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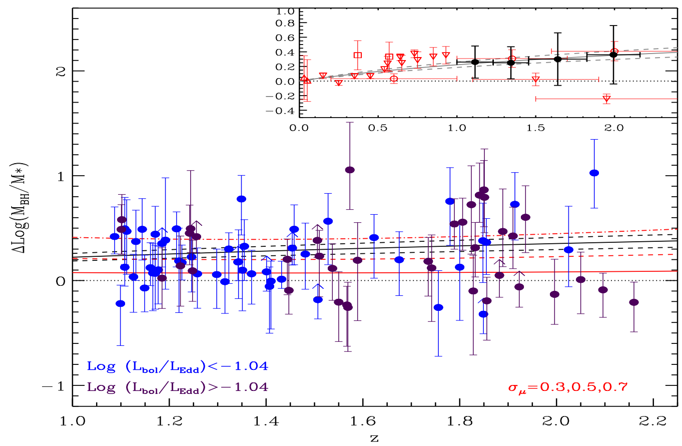

FIGURE 3. Redshift evolution of the offset measured for our type–1 AGN from the local $M_{\rm BH} - M_*$ relation. Different colors identify different ranges of Eddington ratios with upwards arrows representing upper limits on the host mass. The offset is calculated as the distance of each point to the Häring and Rix [25] correlation. Solid black line shows the best fit obtained assuming an evolution of the form $\Delta{\rm Log}(M_{\rm BH}/M_*)(z) = \delta_2{\rm Log}(1+z)$; for which we found $\delta_2 = 0.74 \pm 0.12$. The red lines show the bias due to the intrinsic scatter in the scaling relation to be expected even if they are universal. Solid line is for an intrinsic scatter of 0.3 dex; dashed of 0.5 dex; dot-dashed of 0.7 dex. The inset shows a comparison with literature results. From Merloni et al. [24]

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